Design of a Crushing and Agglomeration Process for Manufacturing Bagasse Charcoal

by

Victoria Y. Fan

Submitted to the Department of Mechanical Engineering
In Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science

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ABSTRACT

In Haiti, wood and wood charcoal are common fuels for cooking. This practice has contributed to deforestation, leading to erosion and fatal floods. The availability of charcoal made from a different source other than wood, such as agricultural waste, might provide Haitians with an alternative, more sustainable fuel, which in turn may reduce fuel prices. MIT students have developed various methods for producing charcoal out of simple inexpensive devices. In a current manufacturing process, carbonized bagasse is crushed to a powder, then mixed and agglomerated with yucca binder into balls. A novel method may reduce operator exposure and inhalation of charcoal fines by keeping primary manufacturing phases in the oil drum and reducing the operational steps of transferring the material from one location to another. The goal of this thesis was to understand, test, and optimize the parameters of this novel crushing and agglomeration process. The final prototype was found to effectively crushing charcoal and mix charcoal with binder to some extent, while being an inexpensive alternative to reduce overall charcoal exposure. However, the mixing and agglomeration was not sufficiently uniform and further designs should be considered to increase uniformity of mixing of binder and charcoal.

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1. Introduction

In developing countries, cooking fuel is essential to daily living. In Haiti, a country already suffering from severe deforestation, finding a fuel source other than wood and wood charcoal may lessen the effects of environmental degradation and also provide an alternative, affordable source of charcoal[1,2]. Furthermore, charcoal burns more cleanly than wood and is better for human health than other non-carbonized sources of fuel.

One alternative charcoal manufacturing methodology, developed by Shawn Frayne, Amy Smith, Jessica Vechakul, and other MIT students, uses bagasse, a sugarcane waste material[3,4,5]. Though with great potential, this process, however, requires operators to transfer the material from one location to another for each step in manufacturing. A newer method developed by Amy Banzaert conducts major steps of the manufacturing process all in the same oil drum. Consequently, this method may significantly reduce the risk of charcoal dust inhalation for operators, and improve the handling characteristics of the briquette material, thereby reducing the number of machines and handling steps involved.

The process has not been optimized, however, and requires further design, study, and testing. The goal of this undergraduate thesis is to understand the relationships of the drum characteristics, speed of rotation, the ratio of water, yucca material, and charcoal, and other aspects of the process as it affects the production of charcoal small "balls".

The goal of this thesis was to design specific machinery and methodologies that are constrained by the new working concept to better understand these relationships and limitations of this approach.

1.1 Background

1.1.1 Charcoal as a Fuel Source

Around the world, 2.4 billion people burn biomass for cooking and heating[6]. Biomass materials include wood, charcoal, raw or processed agricultural waste materials, and dung. Exposure to biomass smoke can cause health problems such as acute respiratory infections (ARI) in children, chronic lung afflictions such as asthma, lung cancer and complications during pregnancy[7]. Charcoal, or carbonized biomass materials, however, is a better fuel source than wood because charcoal burns more cleanly and is smokeless[8]. Furthermore, it can be stored for a longer period of time without degradation.

1.1.2 Energy Use in Haiti

In Haiti, about 90% of households choose wood charcoal[9]. Other data sources suggest otherwise, that rural areas tend to primarily use fuelwood, whereas urban areas tend to use charcoal (Tables 1-1 and 1-2)[10]. Nevertheless, the use of both fuelwood and wood charcoal has contributed significantly to severe deforestation, which has resulted in erosion and fatal flooding[11],[12] (Figure 1-1). Furthermore, the cost of charcoal is prohibitive for the average Haitian. As the supply for wood and wood charcoal becomes increasingly limited because of deforestation, the consequence is an increasing cost of fuel. Thus, the availability of another type of fuel source besides wood and wood charcoal may provide more options for individuals and reduce overall prices[13]. Finding a material other than wood may also lessen the effects of environmental degradation, and provide an alternative, affordable, cleaner and more sustainable source of fuel.

Table 1-1. Modern and solid cooking fuel use in Haiti in 2000[14].

Urban %			Rural %			National %		
Modern	Solid	Total	Modern	Solid	Total	Modern	Solid	Total
7.9	91.9	100	0.7	99.2	100	4.1	95.8	100

Modern cooking fuels include electricity, LPG, natural gas, kerosene, and gasoline. Solid fuels include fuelwood, straw, dung, coal, and charcoal.

Table 1-2. Distribution of women 15-49 by type of fuel used for cooking, by sector in Haiti15.

	Urban %	Rural %	Total %
Electricity	0.0	0.0	0.0
LPG, natural gas	2.9	0.3	1.5
Biogas	1.7	0.2	0.9
Keronsene	3.3	0.2	1.7
Coal, lignite	0.0	0.0	0.0
Charcoal	86.6	17.9	49.4
Firewood, straw	5.3	81.3	46.4
Dung	0.0	0.0	0.0
Gasoline	0.0	0.0	0.0
Other	0.1	0.1	0.1
Total	100.0	100.0	100.0
Number of women	4655	5499	10154

Figure 1-1: Area of Haiti susceptible to soil erosion because of deforestation[16]

In Haiti, there is an estimated 5.2 million available tons of fuelwood (Table 1-3). In contrast, bagasse has an estimated potential availability of 33,000 tons (Table 1-4) or greater, given that sugarcane agriculture is a major industry of Haiti[17]. That is, the supply of fuelwood is

158 times greater that of bagasse. However, fuelwood harvesting is not sustainable, while bagasse supply is renewable each year. Nevertheless, any available alternative fuel source, such as bagasse charcoal, would alleviate the burdens of fuel costs to some extent. Furthermore, sugarcane is the major agriculture in Haiti,

Table 1-3: Land area, forest area and fuelwood production, 1999[18]

	Total Land Area	Forest Area	Fuelwood Production
	Thousand square km		Million tons
Haiti	28	1	5.2
Total North America	21370	5493	116.8
Total World	130484	38616	1443.7

Table 1-4: Estimated potential availability of bagasse, 1999[19]

	Cane sugar production	Bagasse potential availability
	Thousand tons	Thousand tons
Haiti	10	33
Total North America	16957	55279
Total World	98821	322156

1.2 Prior Art: existing charcoal manufacturing models

1.2.1 Western Charcoal Production

Generally, there are two basic methods of making charcoal, direct and indirect. The direct method uses heat from incomplete combustion of the organic matter that provides for the heat for pyrolysis or carbonization of raw biomass to charcoal. The rate of combustion is controlled by regulating the amount of oxygen allowed. The process is stopped by eliminating oxygen before the charcoal begins to burn.

In the indirect method, an external heat source, which requires an additional fuel source, is applied to a closed but vented airless chamber, called a retort. This retort is usually some kind of a metal furnace. The indirect method results in a higher yield of high quality charcoal with less smoke and pollutants and requires less smoke and pollutants. It is generally easier and requires less attention than the direct method[20].

These production methods usually produce wood charcoal of sufficient density for use; this charcoal does not require crushing and then agglomeration. Briquette charcoal, however, by definition is the use of crushed charcoal that is then agglomerated with a binder with high pressure.

1.2.2 MIT Charcoal Manufacturing for Haiti

In rural areas of Haiti, Amy Smith and D-Lab IAP 2003 students observed that by using an alternate source of biomass to produce charcoal, they may help to reduce further environmental degradation[21]. They developed a charcoal production method using bagasse, an agricultural waste product from sugarcane processing. Further work developed the briquette press to avoid practice of hand-formed briquettes[22]. Bagasse should not be burned directly in households because it does not burn cleanly, like many other biomass materials[23].

By using materials that would have otherwise been thrown away or burned to clear space, households could not only recycle agricultural waste, but also provide an alternate source of fuel. The use of this method may also slow down the rate of deforestation in the country. Although this concept was not entirely new, Amy Smith and her team developed a method appropriate for the available materials and skills for rural Haiti. Related research has shown that other types of agricultural waste, such as peanut shells, coconut husks, corn cobs, and saw dust, can be converted into charcoal by employing similar techniques[24].

That MIT team developed a process by which bagasse could be transformed into charcoal briquettes by using a simple oil drum kiln and a binder made from cassava. Cassava is a root crop, also known as manioka, and is a relatively robust crop that can be grown relatively easily in infertile soil. Cassava is widely available in rural areas of Latin America and Haiti. Tests of these briquettes showed that the new 'sugarcane charcoal' did not produce smoke and heated food sufficiently[25].

With the input of several other MIT mechanical engineering students, the process has been developed to produce higher quality briquettes. The original method is taken from "Fuel from the Fields: A Case Study of Sugarcane Charcoal Technology," with latest student developments in italics:

Making the kiln: Ventilation holes were cut in an empty 55 gallon oil drum. These holes allow air to flow through the kiln as the fire gets started and then can be sealed off to provide the low-oxygen environment necessary for carbonization.

Carbonizing the bagasse: The drum was filled with dried bagasse and ignited. When the proper temperature was reached, which is indicated by a change in the color and quantity of smoke produced, the ventilation holes were sealed. After several hours, the bagasse was converted into charcoal.

Forming the briquette: The carbonized bagasse was moistened and then crushed into a powder. A binder was made by boiling grated cassava root to form a sticky porridge. The binder was mixed with the charcoal dust and then hand-formed into briquettes.

Extrusion: Currently, briquettes are no longer formed by hand. MIT students in the 2.009 Product Engineering Process class developed an extruder that took mixtures of binder and charcoal powder into briquettes; the briquettes required further pressing[26].

Compressing: Pressed briquettes have a higher density, and therefore have a higher energy density, thereby allowing the briquettes to burn longer[27].

Drying and Hardening: After drying in the sun for about a few days and then baked from the heat given off from the oil drum kiln, briquettes harden considerably and are ready for use.

1.2.3 New Proposed Manufacturing Method

A new proposed charcoal production method may significantly reduce the risk of charcoal dust inhalation for operators, and improve the handling characteristics of the briquette material. Rather than transferring the carbonized bagasse from one oil drum to other machines or locations to crush, agglomerate, and briquette the material, this model may allow for both crushing and agglomeration in the same oil drum used for carbonization.

In particular, it was serendipitously discovered that by turning a small-scale drum mock-up, balls of charcoal automatically formed or "agglomerated." These charcoal "balls" did not have sufficient density and required further pressing. Moreover, not all charcoal fines agglomerate into balls and the agglomeration process were not consistent. Furthermore, specific parameters of spinning and binder ratios in relation to the quality of agglomeration and briquettes were not well-understood. Finally, it was not understood how a small-scale model would translate in practice for the real-scale oil drum.

1.3 Thesis Objectives

The question this thesis attempts to address is, "How can we optimize the characteristics of the formation of charcoal balls?" The goal of this thesis is to understand the relationships of the drum characteristics, speed of rotation, the ratio of water, yucca binder, and charcoal, as well as other aspects of the process as it affects the production of charcoal "ball-like" briquettes in order to understand if and how this agglomeration process may replace existing extrusion and pressing prototypes. This thesis involves two general phases: (1) the selection of design criteria and the design of prototype and (2) the testing of specific parameters of the prototype.

2. Design Process

2.1 Design Constraints and Criteria

2.1.1 Existing Constraints

There were two primary issues of the existing process: the number of operational steps in transferring bagasse, and the associated health risks from charcoal dust inhalation. Consequently, the constraint that served as the basis of the design process was to keep the process in a 55-liter oil drum that can easily be used for three phases of the manufacturing process: the carbonization phase in the kiln, the crushing phase, and the agglomeration phase. Furthermore, this design must also be practical for testing specific parameters of the crushing and agglomeration process.

2.1.2 Description of Design Criteria

Table 2-1 lists primary design criteria that motivate this thesis. Concern for ease of operation contained within the oil drum, reduction of exposure to charcoal fines, and ball or briquette quality are the primary design specification. The other criteria (cost, maintenance, materials) are common criteria for design for "intermediate" or "appropriate" technologies.

Table 2-1: Design Criteria for Crushing and Agglomeration Processes

Design criteria	Description
Operational steps	The crushing and agglomeration phase is after the carbonization phase. The transfer from carbonization to crushing and agglomeration needs to be easily connected.
Ease of operation	Other parameters include minimal human force required to operate, minimal operational steps required, and minimal time required to produce balls
Safety	Reduction of operator's exposure to charcoal particulates and other safety concerns
Cost	Fewer parts and simpler manufacturing results in lower cost with little or no additional costs to the existing oil drum kiln.
Maintenance	Locally repairable
Materials	Locally available and accessible and durable
Ball/Briquette quality	Ball/briquette quality depends on a number of factors, but the primary concern is if balls/briquettes will have a consistent ratio (of water, yucca binder, and charcoal), and sufficient density. Other parameters (which will not be evaluated in this thesis) include moisture weight and heat value.

2.2 Strategies and Concepts

2.2.1 Initial Mock-Up and Ideas Generation

An initial mock-up of a turning drum had been built by Amy Banzaert and Shauna Mei with a Poland Springs water dispenser jug on a shaft. First, a crushing rod made of a steel metal pipe was placed in the jug as the jug turned, thereby crushing charcoal pieces into a powder. Next, the crushing rod was removed, and yucca binder was added. It was unintentionally observed that the mixture of bagasse charcoal powder and binder formed balls by turning the drum (Figure 2-1). The initial crushing and agglomeration protocol suggested a limited number of parameters to adjust and optimize (Table 2-2).

Figure 2-1: Image of Initial Mock-Up of Small-Scale Model

Table 2-2: Outline of Initial Crushing and Agglomeration Protocol

Phase	Description
Crushing	Place crushing rod in jug and seal jug. Spin jug for about 15 minutes to achieve some charcoal fineness. Remove metal rod and visually approximate amount of charcoal
Binder Preparation	Initial binder ratio was 10:1 ratio of water to yucca powder. Initial binder to charcoal ratio was 1:5 ml/g. Yucca powder needed to be mixed with some water to create a solution before adding to the pot of boiling water on medium heat. Mix continuously to prevent binder from burning.
Agglomeration	Add binder solution to drum and spin drum for about 15 minutes to achieve some level of agglomeration.

Based on this initial model, several process variables were observed: crushing time, crushing fineness, ingredients ratio, ingredients preparation, spinning speed, spinning time, agglomeration percentage (Figure 2-2).

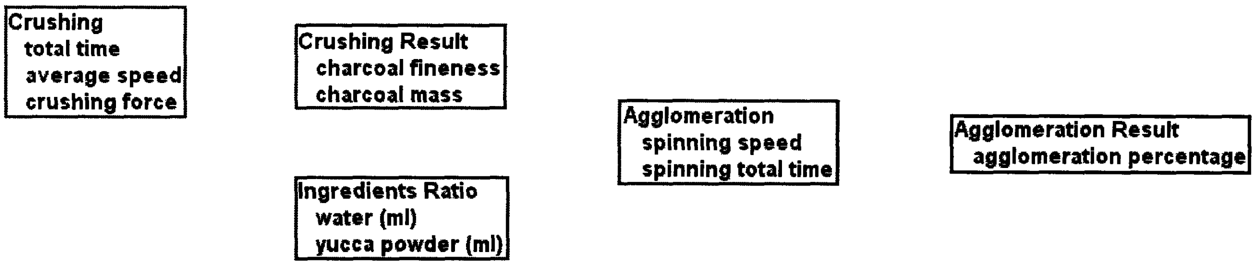

Figure 2-2: Input and Outputs of Initial Manufacturing Process

This mock-up, however, was only a possible method for crushing and agglomeration process. Consequently, the thesis was not limited to this initial mock-up and manufacturing protocol, but could be altered. Consequently, the design process was completed for these two processes and concepts fulfilling the design criteria were generated and compared against each other.

2.2.2 Crushing Process

For the crushing process, several ideas were generated and two major strategies were examined (Table 2-3, Figure 2-3). Major concerns included minimizing the number and difficulty of operational steps required from carbonization to crushing, and reducing charcoal dust exposure for operators. By looking only at the crushing process without looking at the agglomeration, both concepts seemed reasonable, though the mortar-pestle model seemed to have some difficulty in maintaining a more dust-free environment.

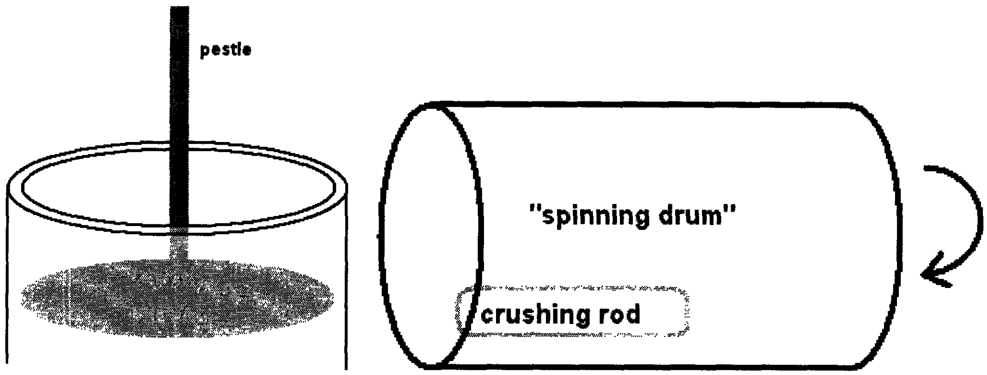

Figure 2-3: Concepts for Crushing Process

Table 2-3: Concepts for Crushing Process

The Pestle: Pestle or plunger with large surface area through top cover used to mash bits	*The Spinning Drum*: A spinning drum with crushing balls by spinning a rod or on bearings
• Challenges: - More energy lost compared to spinning drum - Cost of plunger - Difficulty of mashing - Manufacturing precise hole/rod diameter clearances - User exposure to charcoal if the hole is too large - Drum orientation for agglomeration	• Benefits: - May not lose as much energy as crushing • Challenges: - Potentially slower rate of crushing - User exposure to charcoal from hatches - Drum orientation for agglomeration - Crushing balls or rods would need to be recollected before agglomeration.

2.2.3 Agglomeration Process

For the agglomeration process, several ideas were generated and two major strategies were examined (Table 2-4, Figure 2-4). Major concerns were again the transfer and operational steps required from crushing to agglomeration, charcoal dust exposure, and the preparation and optimal ratio of ingredients.

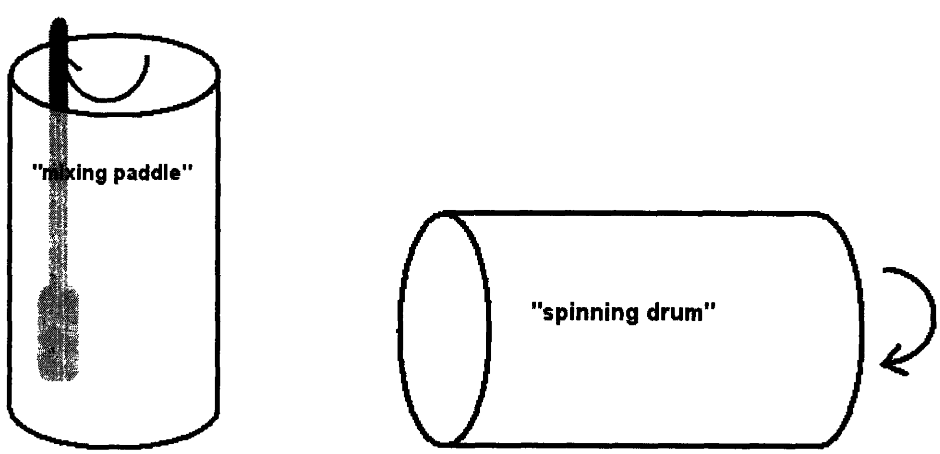

Figure 2-4: Concepts for Agglomeration Process

Table 2-4: Concepts for Agglomeration Process

The Mixer: mixing and mashing rod of vertical drum	*The Spinning Drum*: spinning drum agglomerates balls
• Benefits: - No need to orient drum - Simpler • Challenges: - Cost of mixing rod - May be more labor intensive - User exposure to charcoal dust - Would not produce briquettes, but general agglomerated mass	• Benefits: - Could produce briquettes or balls - Possible free hand to modulate timing of binder adding • Challenges: - May not efficiently and uniformly mix - May require corrugated walls? - Requires drum orientation - Must remove crushing rod (used in crushing)

2.2.4 Selection of Best Strategy

Based on the strategies for both processes for crushing and agglomeration (Tables 2-3, 2-4), the spinning drum appeared to be the most promising concept (Table 2-5). The Masher and The Mixer were considered as one entity, while The Spinning Drum was considered another entity. The Masher/The Mixer combination was used as a reference and +/0/- were assigned based on bench-level experiments with the initial mock-up. Despite the simplicity of the masher/mixer, the spinning drum would require less human effort, would have less operator exposure to charcoal, and could potentially form briquettes.

Table 2-5: PUGH chart comparing two major combined strategies

Specification	The Masher/The Mixer	The Spinning Drum
Ease of orientation	0	-
Cost	0	-
Human effort required	0	++
Exposure to dust	0	+
Briquettes	0	+
Charcoal fineness	0	0
Uniformity of mixing	0	-
Total	0	+ 1

2.3 Proposed Final Design

For the spinning drum, three concepts were considered and compared against each other (Table 2-6): (1) spinning drum with shafts welded on top and bottom with bearings on a stand; (2) spinning drum with shaft through the oil drum, and (3) spinning drum on two shafts with ball bearings. Major concerns included issues of manufacturing an oil drum that could also be used for the carbonization phase, exposure to charcoal dust, and ease of adding a pedal power later. Again, each concept was assigned +/0/- and the first concept was set as the reference. Overall, the shaft with welded rods at the top and bottom of the oil drum was selected because of the ease of manufacturing and ease of orientation.

Table 2-6: PUGH chart of final design concepts

	(1) Shaft at ends	(2) Shaft through	(3) Ball Bearings
Manufacturing	0	-	-
Ease of orientation	0	-	0
Constraints from carbonization phase	0	0	0
Human effort	0	0	0
Exposure to dust	0	0	+
Quality of mixing	0	0	0
Ease of adding pedal power attachment later	0	0	--
Total	0	-2	-2

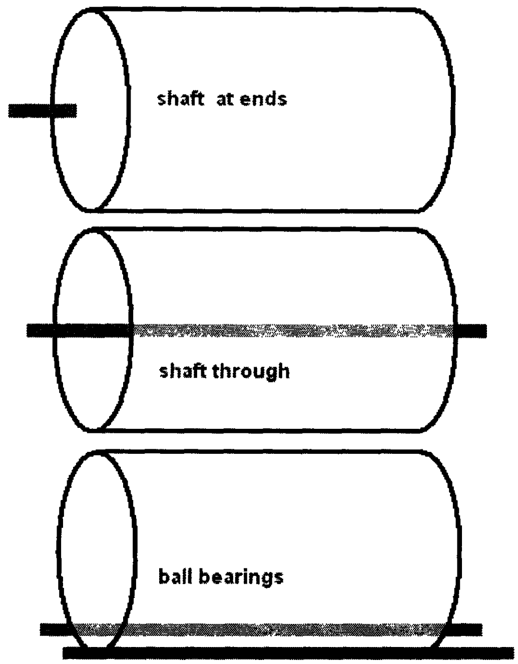

Figure 2-5: Final design concepts

Two steel shafts of an inch diameter and 6" in length were welded to two steel sheets (Figure 2-5b). These two sheets were then aligned and riveted to the top and bottom of the 55-gallon oil drum. PVC bearings were cut to cover the steel shafts and reduce friction between the steel shaft and the wood stand. A wood stand was constructed of two wood planks crossed at the ends (Figure 2-5a). Because the height of the wood fixtures was about 24", this oil drum could be easily picked up and placed on the wood fixtures.

Spinning the oil drum at a rate of up to 1.6 rpm was achieved by hand with ease and without the addition of hoops or turn shafts. Although the height of the stand allowed for easy set-up, a taller set-up would make spinning by hand easier to reduce operator back strain.

Unlike most oil drums, this oil drum had a removable, re-sealable top cap. In developing countries, oil drum either have a removable but not re-sealable top cap, or a top cap welded to the drum. In either case, designs for the hatch were not considered at this stage, because testing and characterization of this spinning was more important.

The method of welding steel shafts to steel sheets had unintended benefits. The connection of the steel shafts to the steel sheets made alignment much easier in comparison to aligning the steel shafts directly on the oil drum. Furthermore, the steel shaft and sheet can be removed and adjusted later in the future if need be. In addition, steel shaft can easily be connected to a pedal power mechanism to increase speed and free the hands of the operators. Finally, the steel shaft welded to the steel sheet was strong and stiff enough to hold the weight of the oil drum on one end (Figure 2-5d). In developing countries, a 6" deep hole could be dug into the ground to allow for the oil drum to be placed evenly on the ground.

In addition to the necessary cost of the oil drum as a kiln, the primary cost of this prototype consisted of the wood for the frame, the 6" steel shafts and steel plates, as well as the cost of welding and riveting.

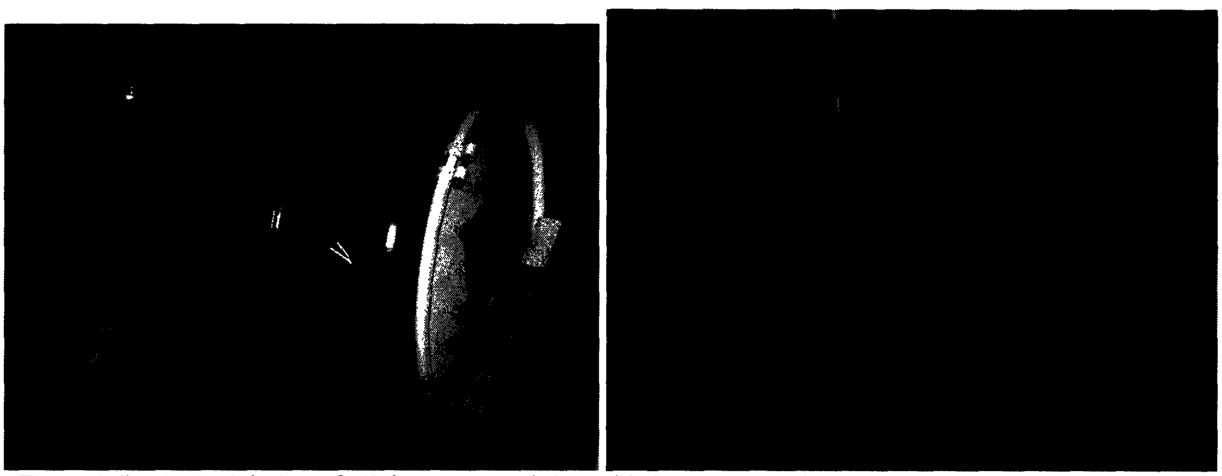

Figure 2-5: (a) Final design of oil drum on stand (b) welded rod to steel sheet plate, riveted to oil drum prior to adding PVC bearings, resting on the wooden stand fixtures

(c) wood stand alone, and (d) oil drum standing on the welded shaft

3. Experimental Procedure

3.1 Overview

Final experimental protocol did not differ greatly from the initial protocol (Figure 2-2). The major difference was that rather than using yucca powder, yucca root was skinned, grated, and squeezed for white milky liquid as a replacement (Figure 3-1). This approach was used because in the field operators will be using real yucca root rather than yucca powder. Second, in some cases, households in El Salvador[28] grated and extract the liquid in order to keep the root for food preparation. Consequently, extraction of liquid does not impact food use because the extracted liquid would have been otherwise thrown away.

The crushing process was first evaluated by measuring the average charcoal fine size through sieves over time at constant speed of 1 rpm. Thus, crushing parameters were established for increasing time and speeds.

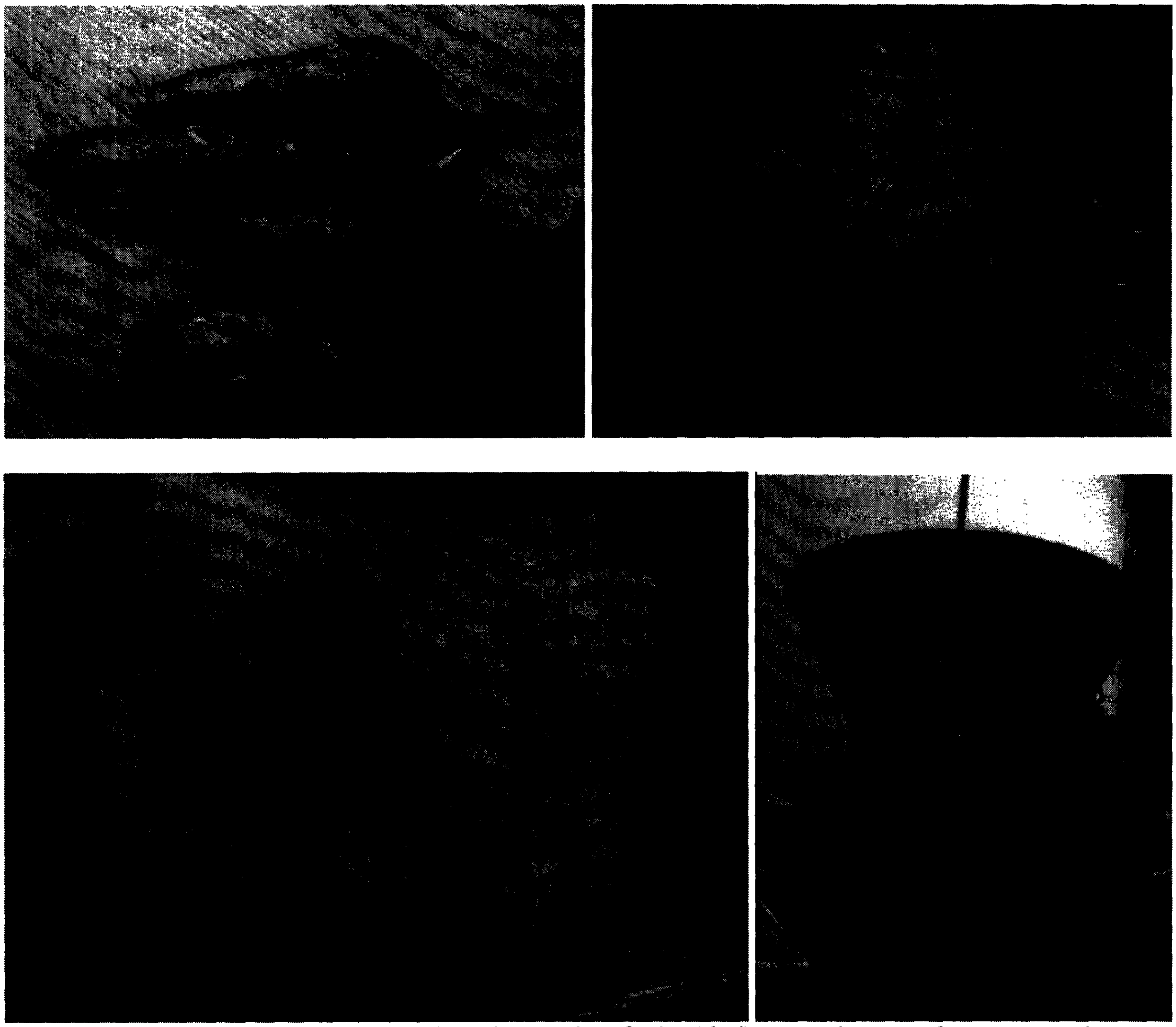

Figure 3-1: Yucca root (a) is grated (b) and pressed (c) for liquid (d) as a replacement for yucca powder.

The agglomeration process would normally be able to accommodate 3000 g of charcoal provided from one run of carbonization. However, it was possible to process a minimum of at least 1000 grams of charcoal in order to simulate conditions of a full load of 2000 g. That is, with less than 1000 grams, charcoal fines and binder would stick to walls without simulating the "balling" effect. There was also a constraint on the available charcoal powder provided by Amy Smith and Amy Banzaert from their trip to El Salvador, as well as the length of time to perform each experiment (4 hours for a single test). Significant time was spent preparing the yucca, as well as specific testing at each time interval after spinning the oil drum.

Yucca liquid was added to boiling water and stirred frequently for three minutes at specified proportions (Figure This binder solution was added to the oil drum with the charcoal and the oil drum was spun at a given speed and checked at regular intervals.

Figure 3-2: Yucca liquid added to boiling water

Agglomeration was observed by a visual presence test and later by a by mass percentage of pieces or balls greater than 4.76 mm in size through sieves. A representative sample from the oil drum was selected and shaken for 10 seconds. Spinning speed and the ingredients ratio were the variables tested to understand their impact on agglomeration percentage. Agglomeration was observed at 5 minute intervals after spinning speed. This resulted in cooling of the ingredients after 5 minutes and may have impacted the agglomeration process after 5 minutes.

All initial tests comparing ingredients ratios and speeds were based on visual inspection, rather than a quantitative measurement of agglomeration percentage. The laboratory space used presented a space for the testing, but important equipment such as sieves, scales, and thermometers were often unavailable because they had been taken and at times not returned.

3.2 Yucca Liquid Extraction

This method of extracting yucca liquid from grated yucca was much more time consuming and labor intensive than simply using yucca powder. In particular, the squeezing of the grated yucca to extract liquid was cumbersome. Consequently, a mosquito net was later used to extract liquid. There was an average of 0.276±0.059 ml of extracted yucca liquid per gram of grated yucca. For 11 samples, a net was used to aid yucca liquid extraction, and for 10 samples no net was used. For yucca extraction with a net, we observe 0.279±0.049 ml/g. Without a net, we observe 0.273±0.070 ml/g.

There was no significant difference in the volume extracted per gram between samples that used a net and samples that did not use a net. However, it appears that not using a net increases the variation of yucca extraction. Furthermore, using a net was faster than extracting by squeezing the yucca with one's fist. For a whole yucca root, extracting liquid with the net required about 20 seconds, whereas extraction without a net required about 100 seconds.. In addition, using a net also prevented yucca root from falling into the container of extracted yucca liquid. Therefore, the net, made of mosquito net and approximately 2 mm wide, is a faster, though not more effective, method of extracting liquid from grated yucca. The mosquito net, however, began to rip if the grated yucca was squeezed too tightly. A more robust, durable material should be explored and considered such as cheese cloth.

Although yucca in El Salvador may be easier to extract liquid from[29], this may not be true of other yucca roots in other countries that may potentially use this method of charcoal manufacturing. One possible cause for the variations in the amount extracted per grated gram is that some of the grated yucca that was weighed was not extracted, as it fell aside before liquid could be extracted from it. In addition, yucca presumably has variations in moisture content as well. Some roots may be drier than others, and therefore have less liquid to begin with.

4. Prototype Testing: Results and Discussion

4.1 Crushing Process

4.1.1 Results

We measured the mass of charcoal of three different sizes: "fine" (less than 2 mm), "medium" (between 2 mm and 4.76 mm), and "large" charcoal (greater than 4.76 mm). Overall, we observe that the percentage of fine as well as medium charcoal increased significantly after 25 minutes (Figure 4-1). Although the percentage of large charcoal appeared to decrease, it did not decrease significantly. Finally, variation of the percentage of fine charcoal and large charcoal decreased over time.

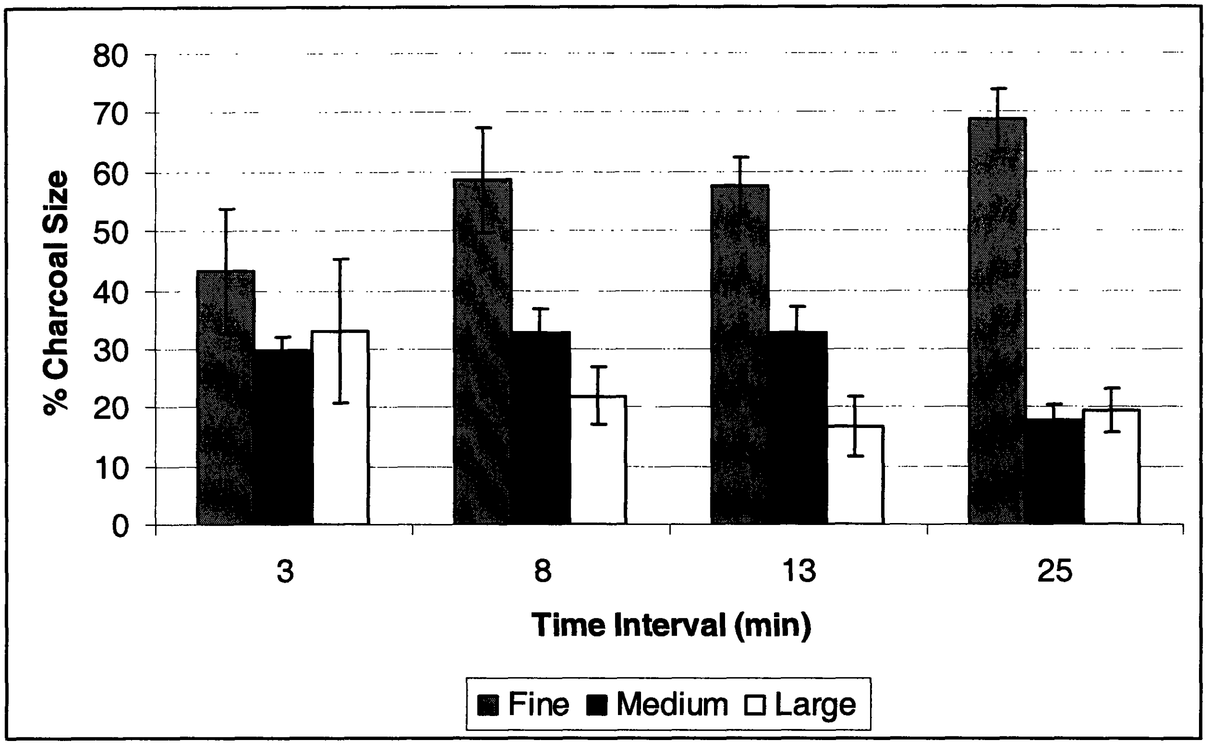

Figure 4-1: Percentage of Charcoal of Varying Fineness over Time

Comparing the ratio of fine to large charcoal at each time interval (Figure 4-2), a significant difference between 3 minutes and 8 minutes was observed. After 8 minutes, the fine to large ratio continued to increase, but there did not appear to be a significant difference between 8 and 13 minutes, and 13 and 25 minutes.

Comparing the ratio of fine to medium charcoal at each time interval, no significant difference from 3 minutes to 13 minutes was observed. However, a significant difference between 13 minutes and 25 minutes was observed.

Comparing the ratio of medium to large charcoal at each time interval (Figure 4-1), significant differences between 3 minutes and 13 minutes, as well as 13 minutes and 25 minutes were observed. There did not appear to be a significant difference between 3 and 8 minutes and 8 and 13 minutes.

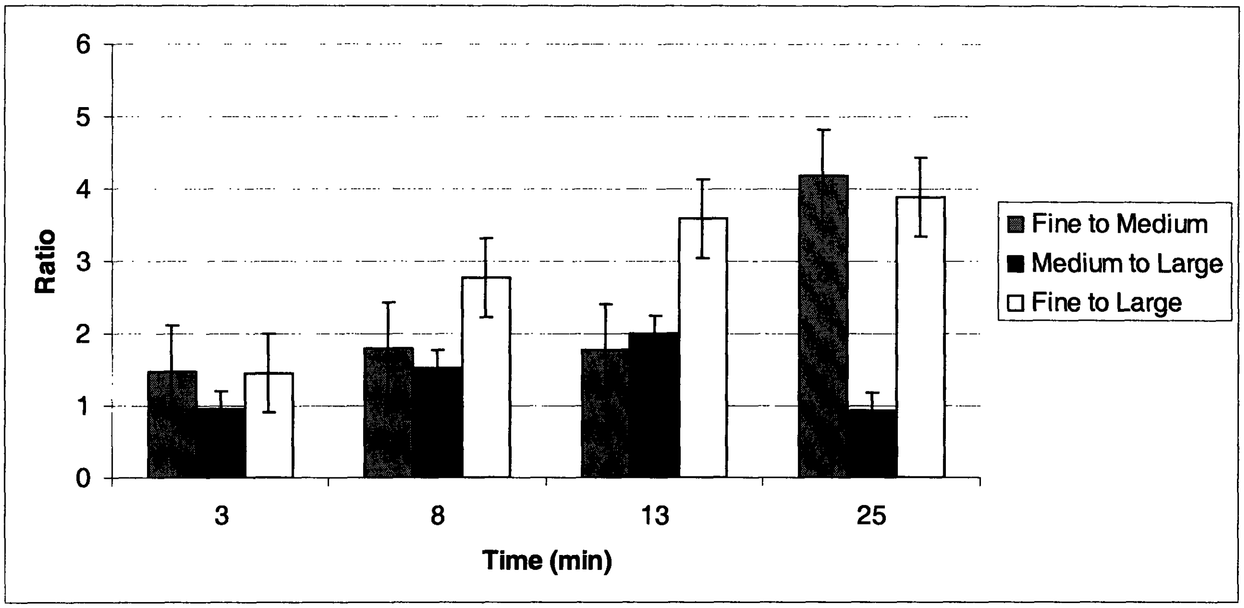

Figure 4-2: Ratios of Charcoal Fineness vs. Crushing Time

4.1.2 Discussion

The results suggested that within 8 minutes of crushing, the amount of fine charcoal compared to the large charcoal fines increased significantly. In addition, within 13 minutes the ratio of medium charcoal fines to large charcoal fines increased significantly as well. Overall, within the first 13 minutes, there was an increase of medium and very fine charcoal compared to the large charcoal fines.

After 13 minutes, however, the ratio of fine charcoal to medium charcoal increased significantly. This suggested that after 13 minutes, crushing more effectively targeted medium charcoal fines than large charcoal fines. This confirmed our observations that after 13 minutes the large charcoal fines consisted primarily of incompletely combusted bagasse that would be more difficult to crush than combusted bagasse.

4.2 Agglomeration Process

4.2.1 Ingredients Ratio

To understand the agglomeration process, three variables were adjusted: ingredients ratio (water, yucca, charcoal), spinning speed, spinning time. The suggested ingredients ratio of 1:4:5 yucca to water to charcoal proved insufficient. In Test 1 at 0.6 rpm, the result was a dry mixture that was not uniformly mixed.

Consequently, increasing the proportion of water and yucca was tested at 0.6 rpm for Test 2. By visual estimation, a ratio of 1:5:3 provided for a more uniformly mixed and goopy mixture that resulted in the presence of some agglomeration. For Test 3, an ingredients ratio of 1:3:2.6 at 0.6 rpm resulted in much more agglomeration than Test 2, which strongly suggested that closer yucca to charcoal proportion rather than water would more aid the agglomeration of balls. However, on a practical level, because yucca is the major cost of this process, limiting the amount of yucca used would be ideal.

Furthermore, in the first few runs, only balls that were smaller than the size of the grooves on the drum wall were found (Figure 4-3) and appeared to be formed in part by existing wood twigs that were not fully carbonized (Figure 4-4). In addition, nearly all balls were observed to be very light. When squeezed, balls would extrude out white liquid, suggesting that the spinning did not uniformly mix the balls at all. This suggested that methods to increase uniformity and mixing of the binder into the charcoal would increase the quality of the balls overall. Consequently, the initial yucca to charcoal ratio of 1:5 was fixed, while the proportion of water was adjusted.


Figure 4-3: Largest available charcoal balls

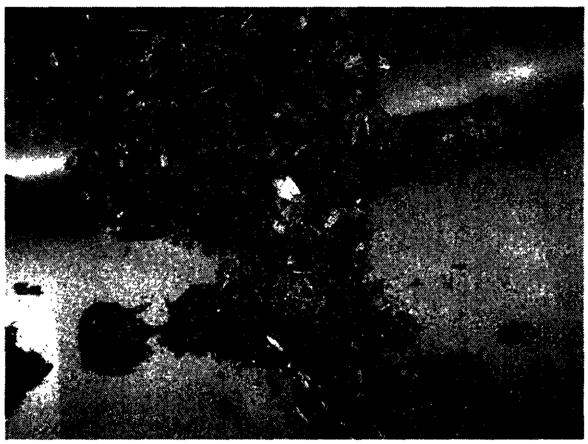
Figure 4-4: Charcoal agglomeration in oil drum

4.2.2 Spinning Speed

Next, two more tests at 1 rpm were tested and by visual approximation the agglomeration mixture appeared to have just as much agglomerated as at 0.6 rpm, if not more. Spinning at a higher speed may increase the uniformity and extent of binder mixing with charcoal. Consequently, later tests increased the speed as much as possible to mix the binder as thoroughly as possible.

4.2.3 Percent Mass Agglomerated

To address the issue of uniformity of the binder solution mixing with the charcoal, two changes were made to the protocol: (1) mixing the total mixture by hand with a long wooden spoon, (2) increasing the water ratio by adding water at every 5 interval of spinning.

Two tests (Tests 6 and 7) were done with the initial ingredients ratio of 1:5:5 yucca to water to charcoal at 1.6 rpm (Figure 4-5). The percent mass greater than 4.76 mm was measured. In Test 6, 250 ml of water was added at each interval. The percentage of agglomerated charcoal increased, but there was no significant difference in agglomeration between any interval. However, the variation in samples decreased at each increasing interval. After 20 minutes an agglomeration of 67.5±5.5% was achieved. Of the proportion of charcoal agglomerated, however, only about 5% was larger than 1 cm in diameter. Most of the agglomerated mass was in smaller pieces.

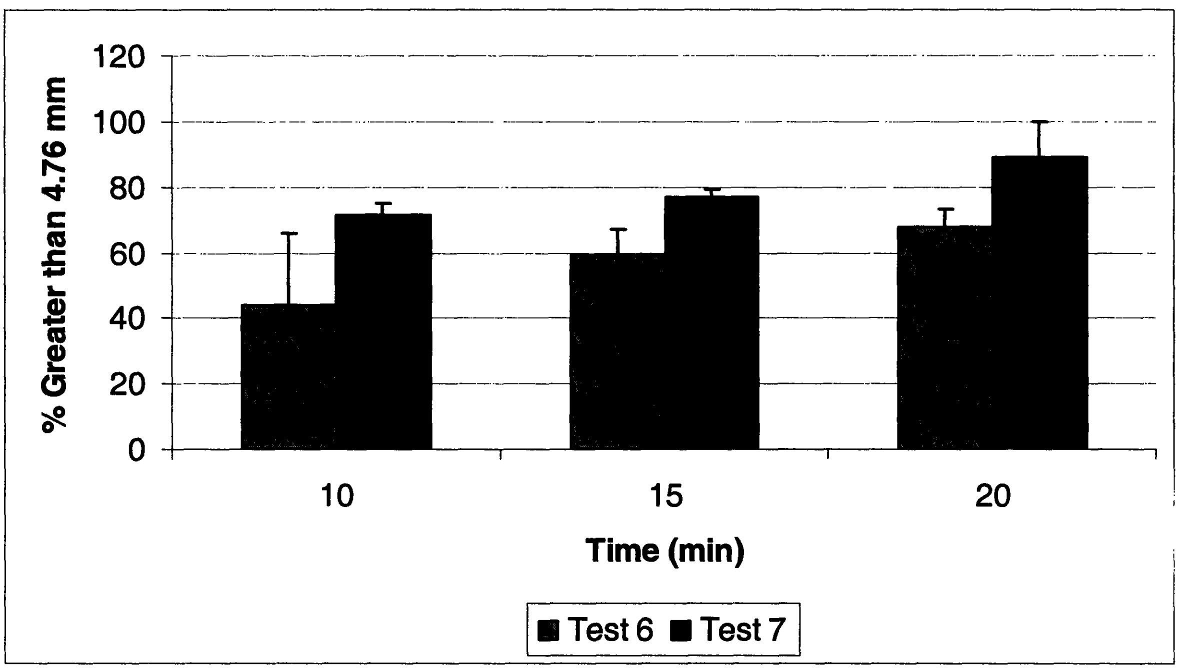

Figure 4-5: Proportion of Agglomerated Mass vs. Time from Test 6 and 7

In Test 7, 500 ml of water was added at each interval, twice the amount of Test 6. The percentage of agglomerated charcoal increased, but there was no significant difference in agglomeration between any interval. Unlike Test 6, the variation in samples did not decrease at each increasing interval. After 15 minutes, an agglomeration of 88.7±11.4% was observed. The overall proportion of agglomerated charcoal of Test 7 was significantly greater than that of Test 6, which suggests that adding more water at each interval increases the agglomeration percentage. However, there were fewer balls greater than 1 cm in diameter from Test 7 than in Test 6. This suggests that there may be a tradeoff in total mass agglomerated with the size of balls.

Finally, two alternative approaches were conducted to increase mixing. First, adding a heavy 2" diameter rod used for crushing to see if that would result in increased mixing. This only flattened out the previous agglomerated balls into flat "coins" and did not appear to increase mixing.

Second, four "template" balls of 4" diameter were formed by hand to see if the presence of balls would increase agglomeration by serving as nucleation sites. After 5 minutes of spinning, all 4" balls had disintegrated and no balls greater than 1" in diameter were found. This suggests the presence of balls do not aid agglomeration and that there may be a limit in the size of balls with respect to a given ingredients ratio. However, dried and hardened ball prior to serving as nucleation sites was not tested and could be a further area of research.

Lastly, remainders of Tests 3-7 were formed into briquettes for further testing for energy density and moisture weight (Figure 4-6).

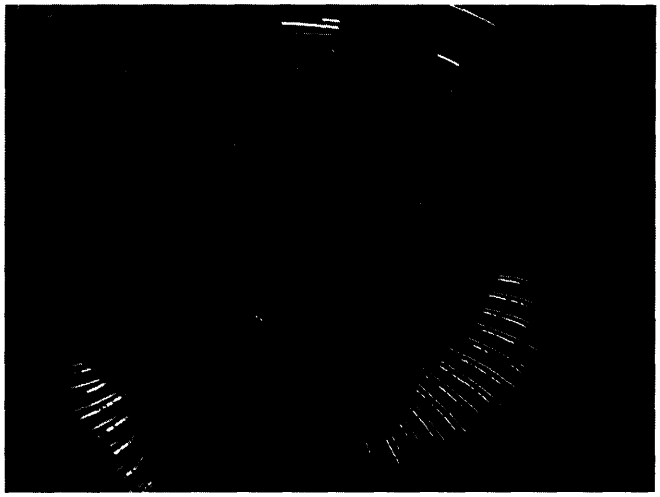
Figure 4-6: Image of charcoal briquettes

5. Conclusion and Future Work

5.1 Conclusion

This goal of this thesis was to develop a model of the bagasse charcoal manufacturing process that reduced operator exposure to charcoal dust inhalation and operational steps involved at transferring bagasse charcoal from one process to the next. Design specifications were identified and a prototype was designed and built. This prototype was tested for its ability to crush charcoal pieces into charcoal dust, and agglomerate charcoal dust with binder.

The crushing process of the prototype is effective, easier, and safer for operators. The agglomeration process, however, is somewhat effective, but did not produce briquettes of sufficient size or density for use. Furthermore, binder did not consistently mixed in the oil drum by spinning and further research into spinning paddles may prove to be a more efficient mixing method. Nevertheless, this process also reduces operator exposure to charcoal dust inhalation and is a cheaper intermediate process method than the charcoal extruder prior to pressing.

5.2 Alternative designs

There were two variables that were not tested in this thesis: the drum diameter and the time at which the binder was added (added all at once in the beginning). Design of a drum that allows for an inner modular diameter may aid with increasing uniformity of mixing. Second, a hatch on the size of the oil drum would allow for the binder to be added continuously or at intervals. Furthermore, the addition of a pedal power to the machine would aid for hands-free operation as well as easy operation of the binder to be mixed continuously or at intervals. Prior art of cooking equipment should be considered, such as a four-armed paddle for mixing as well as crushing. Finally, testing small, dried nuggets that can withstand spinning in the drum may be able to serve as nucleation and agglomeration sites.

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